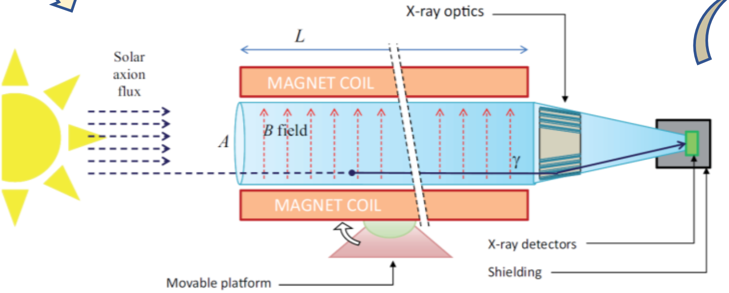
Recoil imaging for DM, neutrino, and BSM physics applications (TPC variations, optical readout)

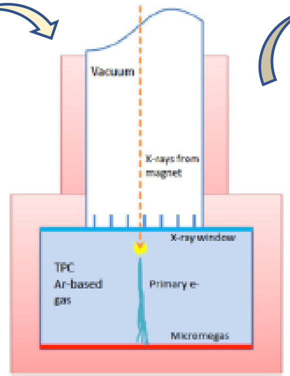
D. González-Díaz (IGFAE)
29-04-2021

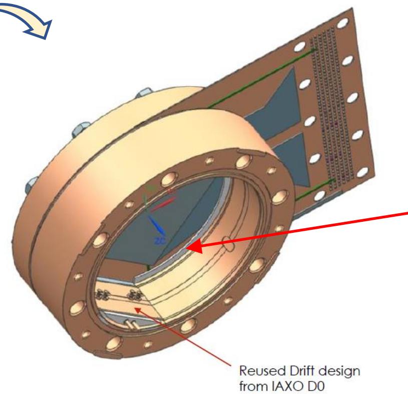
Special thanks to (hopefully I did not forget anyone):

G. Luzón, I. Irastorza, T. Dafni, E. Ferrer, G. Catanesi, L. Arazi, M. Sorel, R. Guenette, B. Jones, F. Monrabal, T. Marrodán, R. Santorelli, N. Spooner, D. Santos, E. Baracchini, W. Dominik, A. Deisting, K. Mavrokoridis, J. Kaminski, I. Giomataris, X. Lu, P. Hamacher, Y. Ayyad, J. Benlliure, P. Majewski, D. Pinci, H. Natal, K. Nikolopoulos, F. Brunbauer

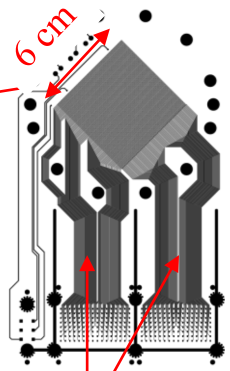
IGFAE
Instituto Galego de Física de Altas Enerxías





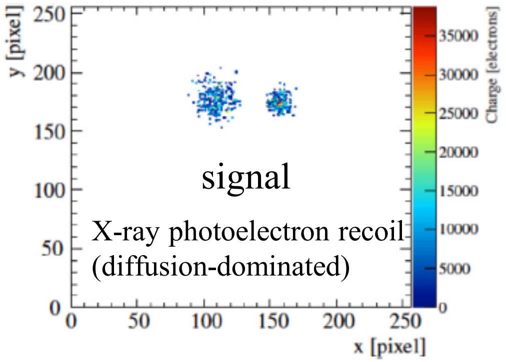


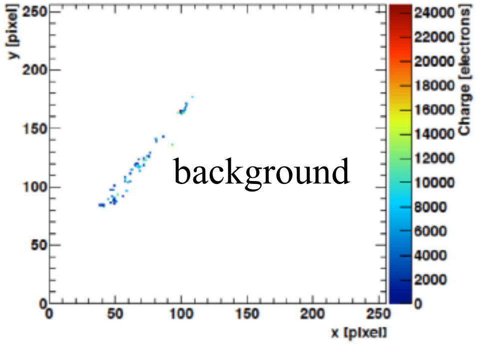
Microbulk Micromegas



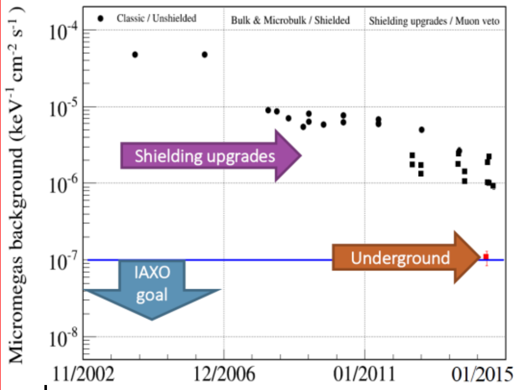
x-y strips

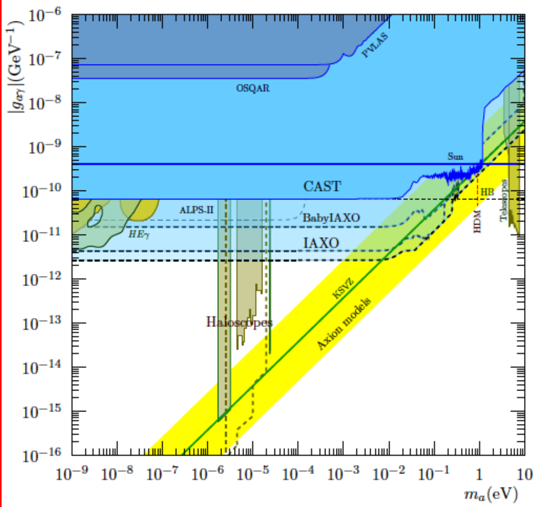
a large-scale enhanced axion helioscope (>10^4 x CAST SNR)

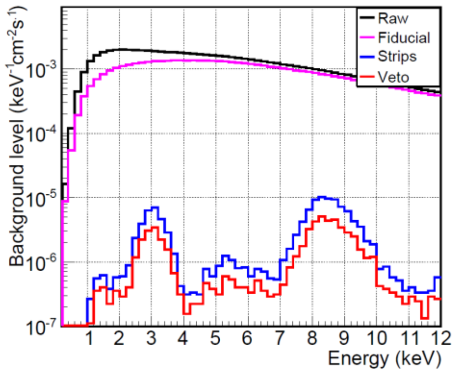




main goal





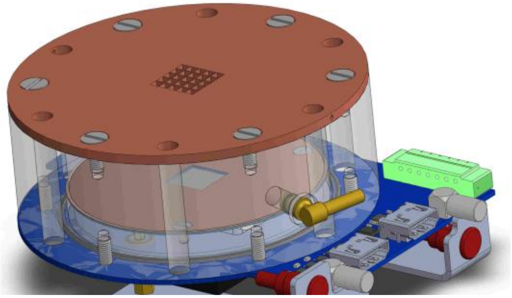


JINST 9 (2014) 9 P01001
JCAP 12 (2015) 9 008
JCAP 01 (2016) 034

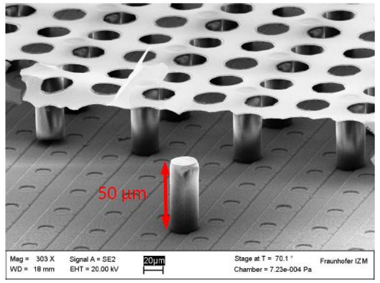
BabyIAXO: intermediate experimental stage before IAXO (>10^2 x CAST SNR): *Abeln, A. et al., arXiv: 2010.12076*

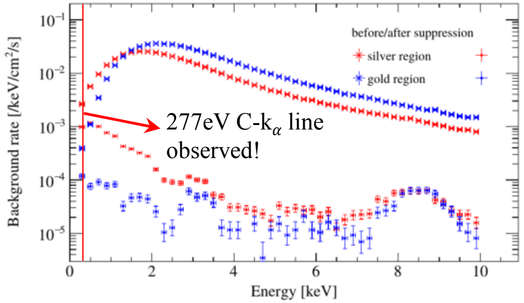
Detector requirements:

- High detection efficiency in the RoI (0-10 keV)
- Very low background needed < 10 keV: 10^{-7} c/keV/cm^2/s (achieved underground!)
  - ➔ shielding
  - ➔ radiopurity
  - ➔ event topologies
- Operation in xenon at around 1bar (higher absorption, suppression of escape-peak)
- Development of radiopure electronics based on AGET.



GridPix





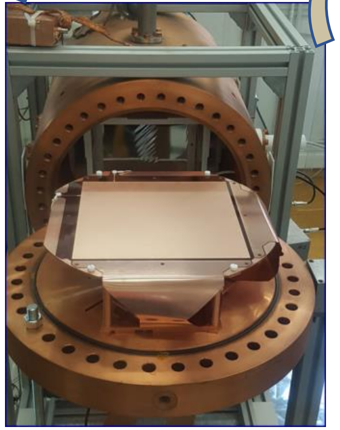
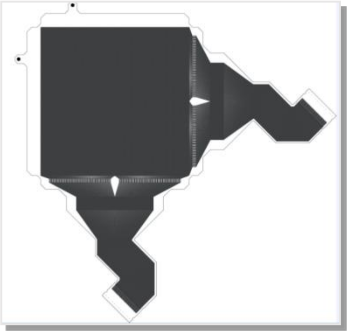
NIM A 535 (2004) 506-510
NIM A 845 (2017) 233-235
NIM A 893 (2018) 26-34

charge-based

TREX-DM

* ERC funded



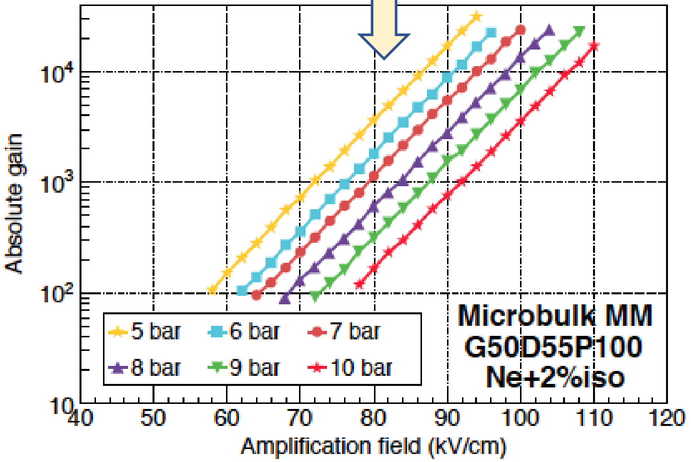
- ➢ 25 x 25 cm^2 Microbulk Micromegas
- ➢ 256 X strips, 256 Y strips,
- ➢ **~1 mm pitch**
- ➢ Sampling rate 50 MHz, 512 samples, window 10.2 ms
- ➢ **Expected event rate: ~10 Hz**

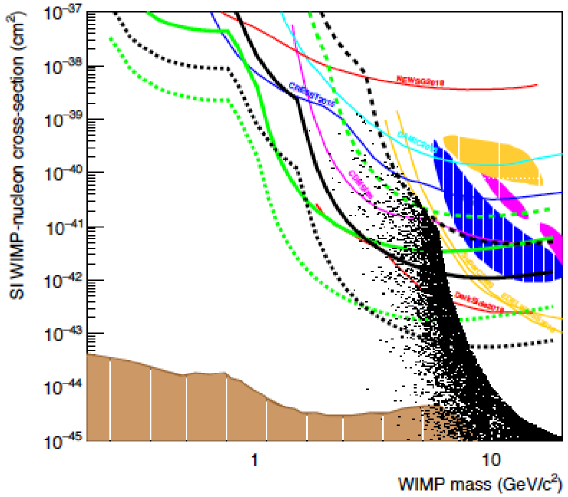
TPC characteristics:

- ➢ Read out technology similar to IAXO.
- ➢ ~20 liters of pressurized gas (~0.16 kg of Ne at 10 bar).
- ➢ Equipped with microbulk Micromegas and AGET-based electronics.
- ➢ Not focused on directionality (operation at high pressure!).
- ➢ Use topological information:
    - Few microns track → nuclear recoils
    - Peripheral or extended tracks→ electron events
- ➢ Low radioactivity techniques to reduce background level: material screening and selection, Rn control, shielding.
- ➢ In commissioning stage at LSC.

Goals:

- ➢ Low energy threshold (< 1 keV) and low background level (~1 c/keV/kg/day).
- ➢ Sensitivity to low mass WIMPs (0.1-10 GeV/c^2) beyond current bounds.





Eur.Phys. J. C 79 (2019) 9, 782

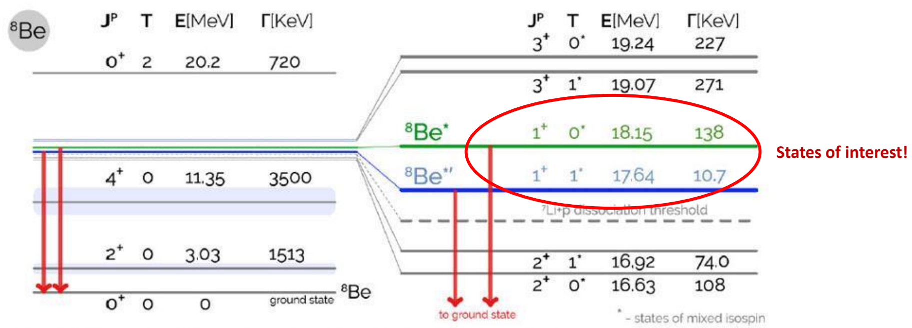
and references therein

charge-based

IEAP CTU in Prague

chasing the X17 boson with a TPC-based spectrometer (IEAP CTU in Prague)

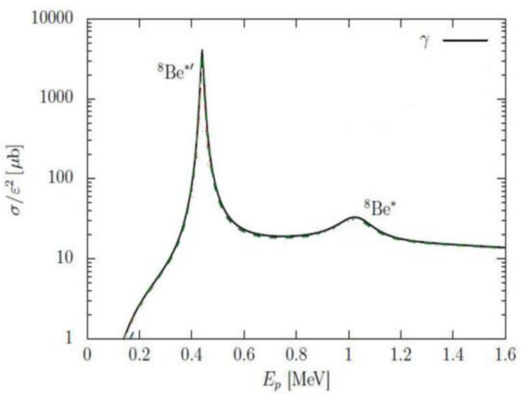
^{8}Be* - Decay Scheme



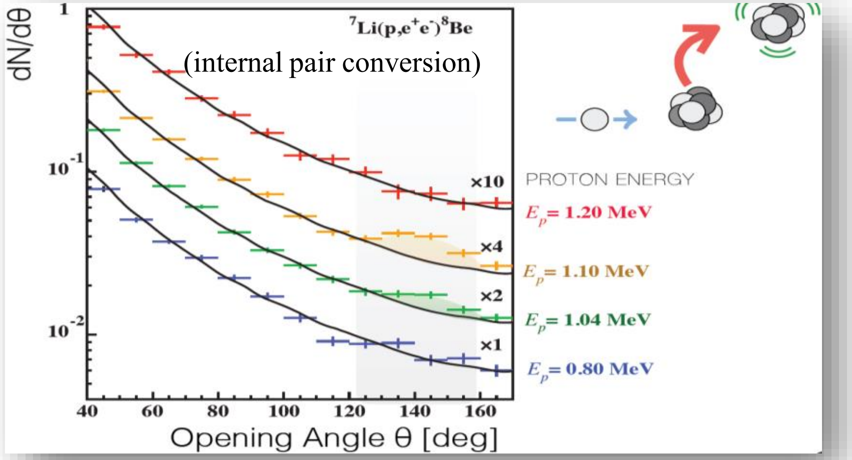
1609.07411; based on Tilley et al. (2004); National Nuclear Data Center, http://www.nndc.bnl.gov/nudat2/

(J. Feng)

cross section vs p beam energy

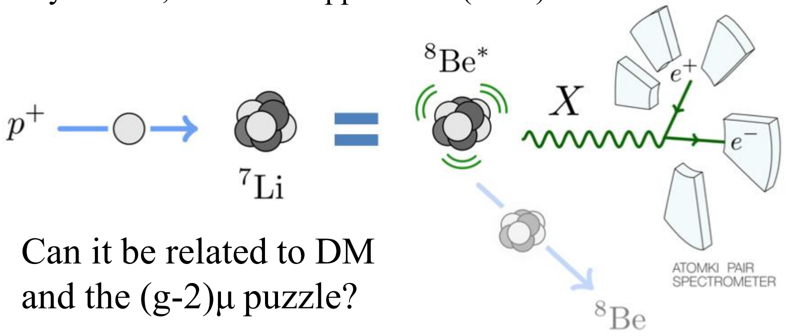


6.8σ peak near **140^0** instead of expected monotonic decrease, **only** at ^{8}Be* resonance.



Krasznahorkay et al. PRL 116, (2016)

Gulyás et al., NIMA 808 pp. 21–28 (2016)



Can it be related to DM and the (g-2)μ puzzle?

Two of the many models developed to explain the 17 MeV boson:

Feng et al. Phys Rev. D 95, 035017 (2017)

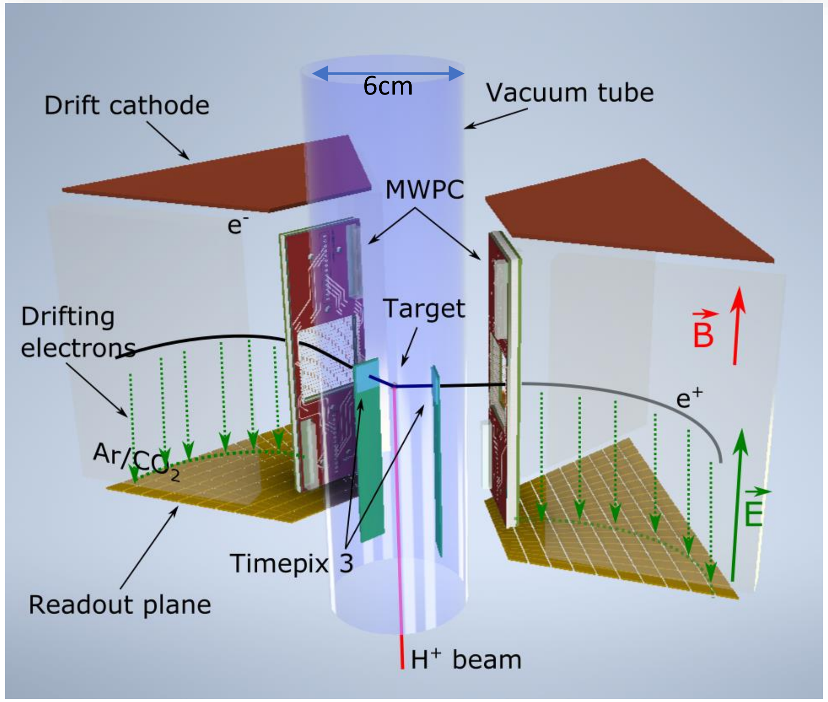
Zhang and Miller, Phys.Lett., Vol. 813, 136061 (2021)

TPC characteristics:

- Superb angular resolution (<1°).
- Good energy resolution (<8%).
- Good position resolution.
- High granularity in a compact setup,
- Large SNR.
- Good timing resolution (<10ns).
- Combination with other technologies.

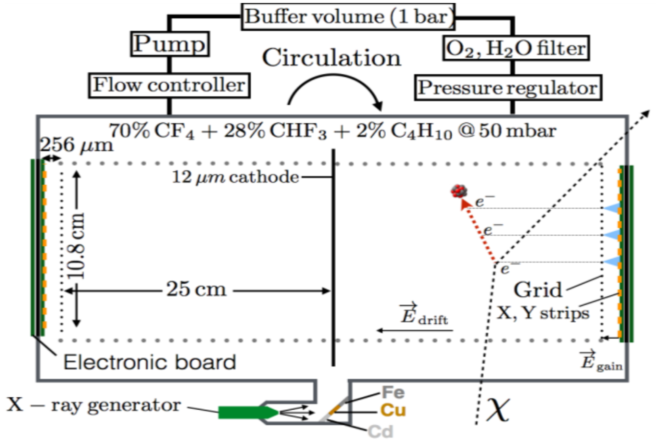
Goals:

- Repeat the experiment with much better resolution

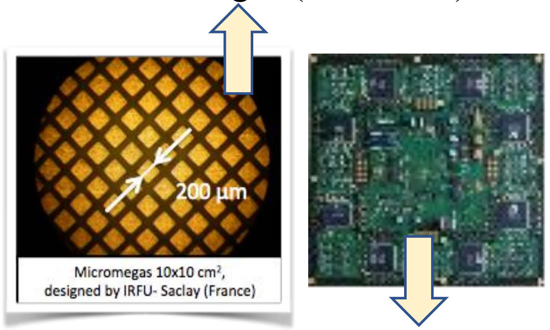


charge-based

MIMAC (Grenoble)



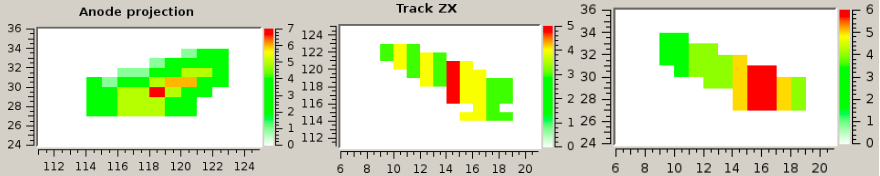
Micromegas (10x10cm^2)



dedicated fast electronics (self-triggered) based on the MIMAC chip (64 channels)

34 keVee recoil in 3D

- Measure dark matter directionality

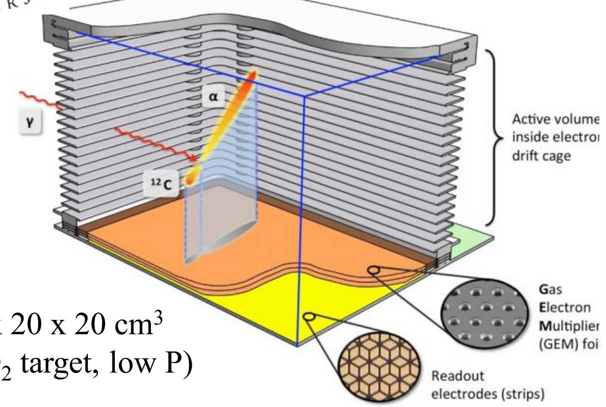


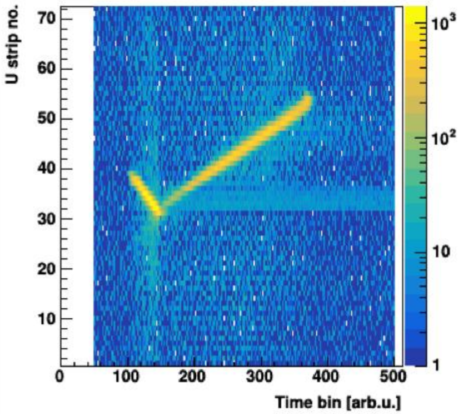
JINST, 12(11):P11020, 2017b

charge-based

study He burning (regulate C/O ratio), ^{18}O burning (regulate ^{16}O/^{18}O ratio)

NIM A 954 (2020) 161779





33 x 20 x 20 cm^3
(CO_2 target, low P)

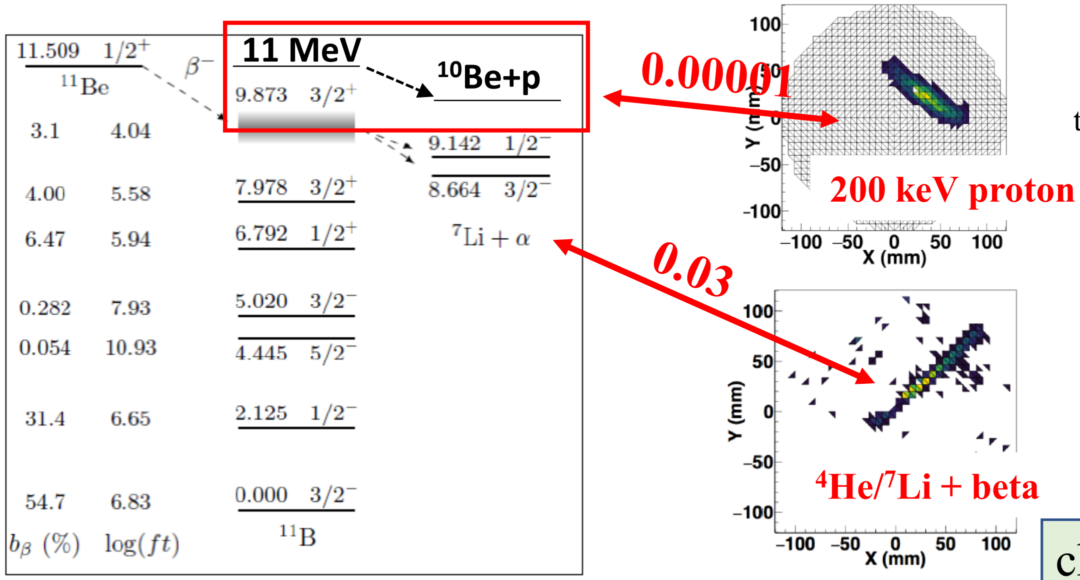
triple-GEM amplification + 3 strip planes + AGET

- Study photo-disintegration reactions (time-reverse of direct capture reactions in stars) with monochromatic, brilliant gamma-ray beams (up to ~20 MeV, VEGA facility, ELI-NP, Romania)

charge-based

AT-TPC (NSCL), '^{11}Be experiment'

Micromegas He+CO_2

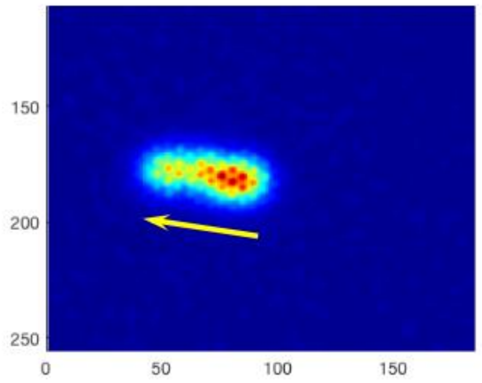


charge-based

n-rich nucleus β-decays emitting a proton?
Phys. Rev. Lett. 123, 082501 (2019)
or
the anomaly can be interpreted in terms of a neutron decaying to a Dark Matter particle?
Phys. Rev. Lett. 120, 191801 (2018)

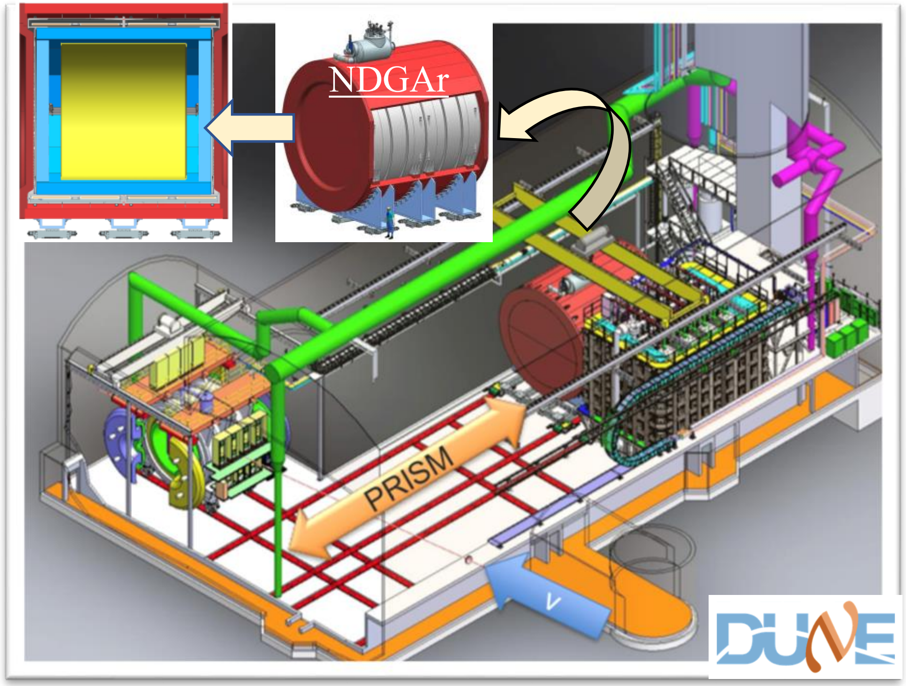
natural evolution: kinematically-complete reconstruction using ^{10}Be recoil (~20keV)

100 keV F recoil

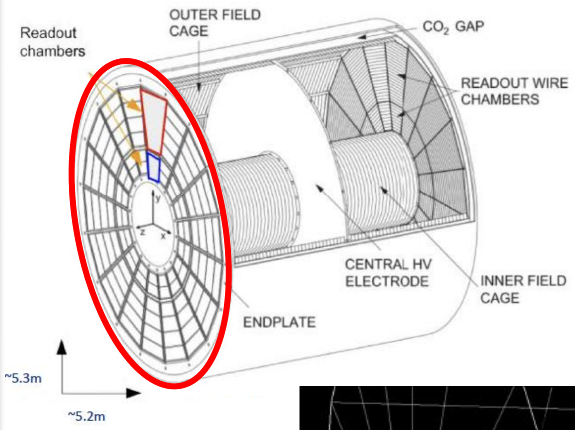


(optically-imaged with camera)

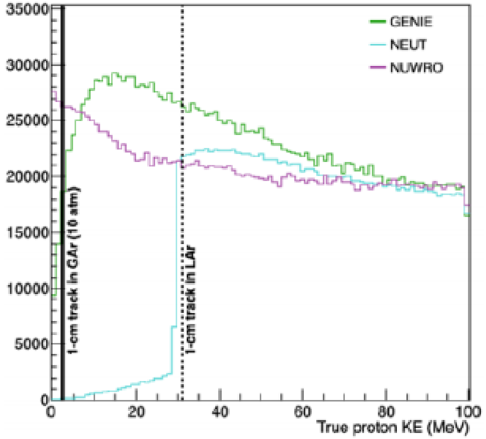
scintillation-based



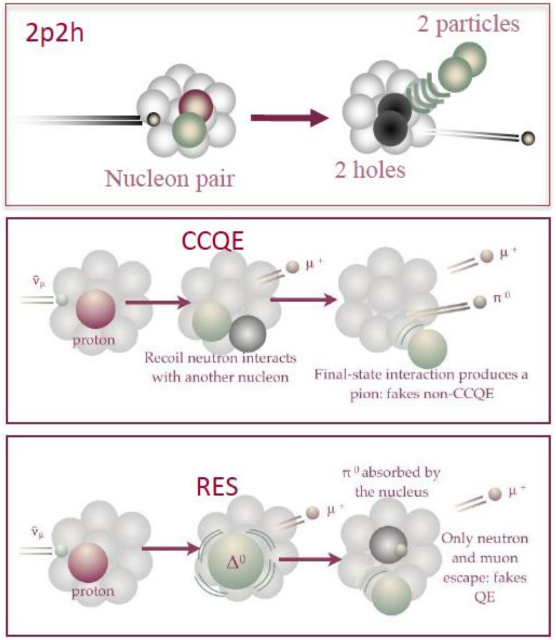
present idea:
refurbish ALICE readout

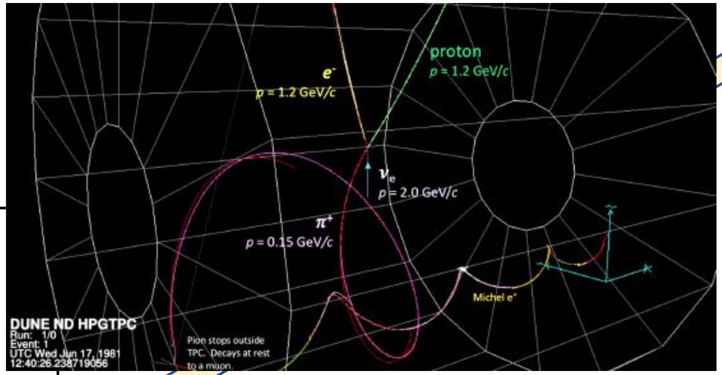


recoil protons from ν-Ar interactions



Nuclear effects in neutrino-nucleus interactions include
- Fermi motion
- FSI (Final State Interaction) breaking up nucleus
- 2p2h





Near Detector Suite has a magnetized high pressure TPC (NDGAr)

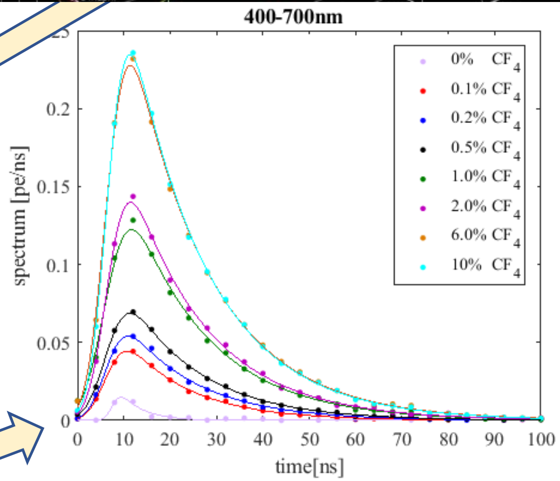
arXiv:2103.13910

Role:

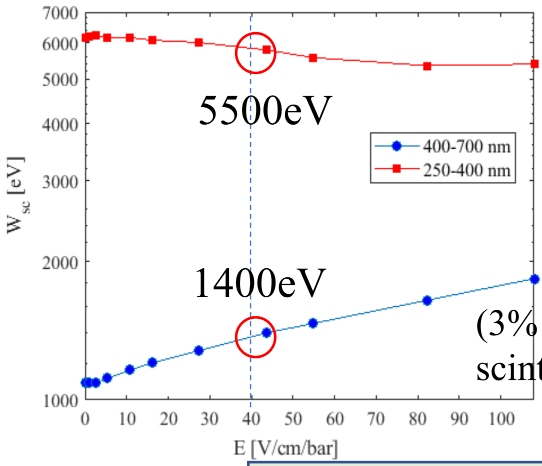
- Tracker for forward-going muons escaping ND-LAr.
- Superb 4π-reconstruction of CC and NC interactions (~1.5M CC evts/yr).
- Address low-energy nuclear physics effects (Fermi motion, FSI, 2p2h).
- Low-energy BSM channels, under exploration.

TPC characteristics:

- Nominal pressure 10bar, E_d ~40V/cm/bar. Read out with wires.
- Tracking threshold 5MeV for protons (improvements ongoing).
- Momentum resolution 2.7% for a typical muon sample.
- *Possibility of using primary scintillation under investigation* (never done for a charge-read TPC in a particle physics application)

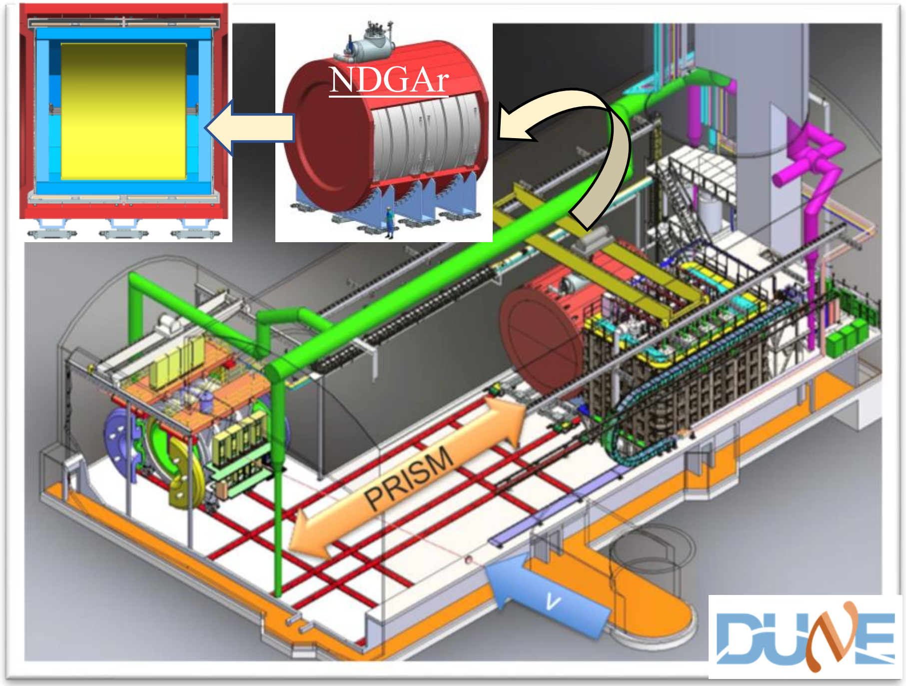


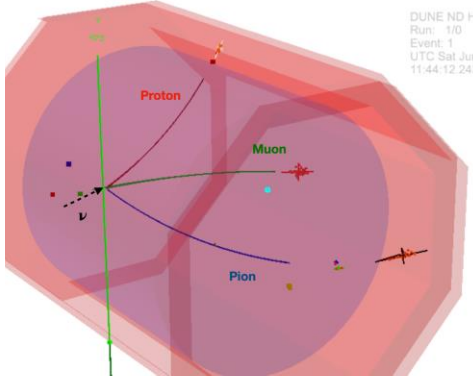
publication in preparation!

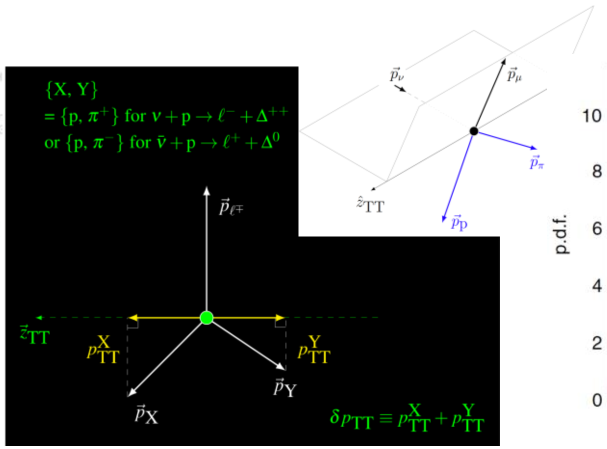


(3% of Ar scintillation)

charge-based (+T_0?)

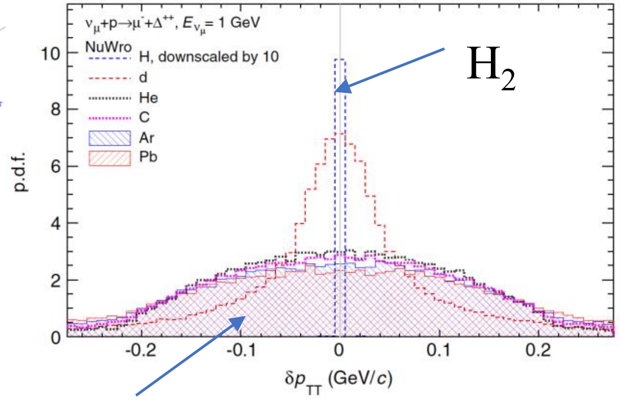






leading channel at DUNE energies:

$$\nu + p \rightarrow \mu^- + p + \pi^+$$
$$\bar{\nu} + p \rightarrow \mu^+ + p + \pi^-$$



transverse kinematic imbalance of heavy nuclei, allows identifying nucleons with Fermi motion (non-H)

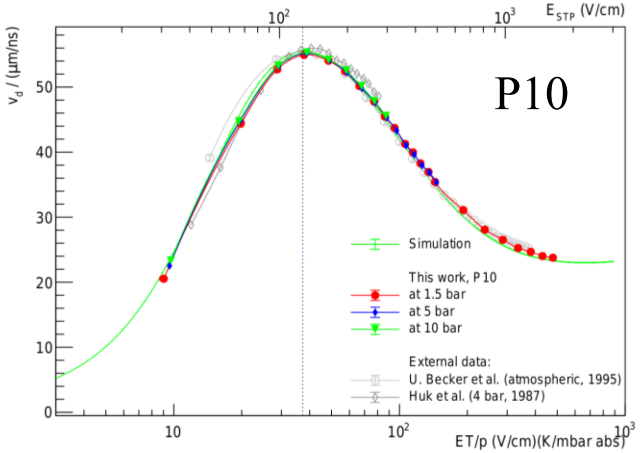
As long as NDGAr works as forward tracker, it could allow other physics programs to run in parallel). One such, is the study ν-H reactions.

Role:

- Tracker for forward-going muons escaping ND-LAr.
- Unprecedented statistics in ν-H interactions with good tracking, and low threshold.

TPC characteristics:

- Nominal pressure 10bar, E_d ~40V/cm/bar.
- Use C_xH_y to enhance H-content (theoretical vapour pressure-limited gas: $\mathbf{C_{3.93}H_{9.86}}$ (= 17% neopentane + 35% i-butane + 24% butane + 24% propane)
- Drift-diffusion coefficients to be measured at high pressure, verify P-scaling!.
- Maximum gain?
- Which readout structure is optimal?



detailed measurements in pure alkanes ongoing

Hydrogen-rich high-pressure TPC

- Why a gas TPC? Why high pressure?
  - Acceptance, tracking threshold
  - Target mass
- Why not others?:
  - Bubble chamber: worse tracking
  - H_2 gas: not hydrogen-rich enough
  - H_2 liquid: too slow
  - CH-based plastics: worse H-content and momentum resolution.

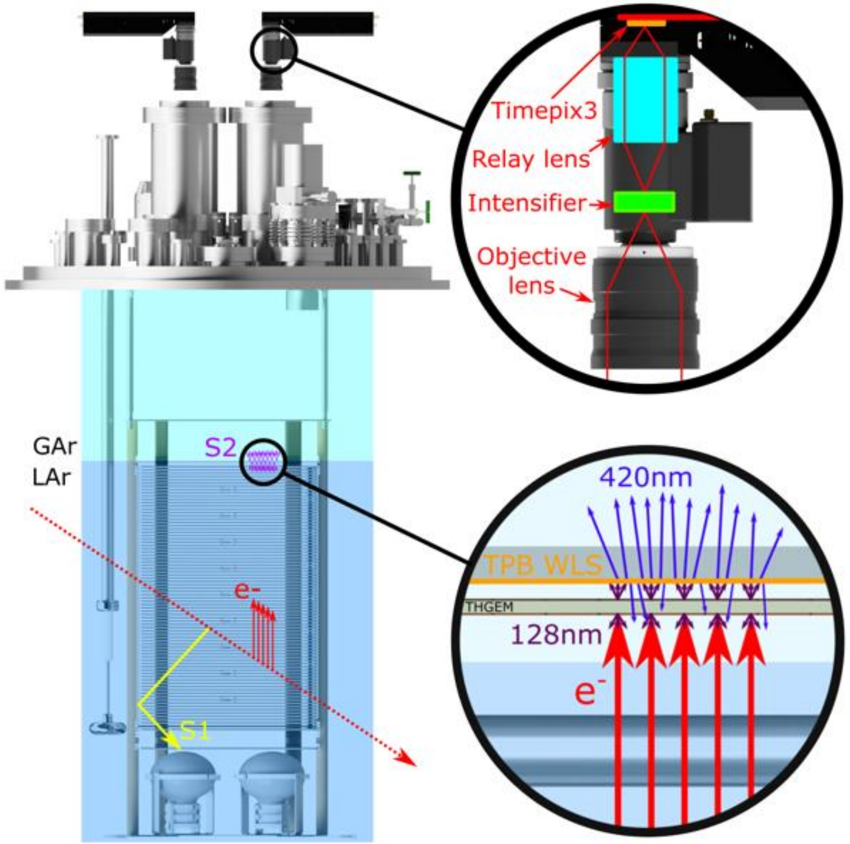
Phys. Rev. D 102, (2020) 033005
Phys. Rev. D 92, (2015) 051302

charge-based (+T_0?)

* ERC funded

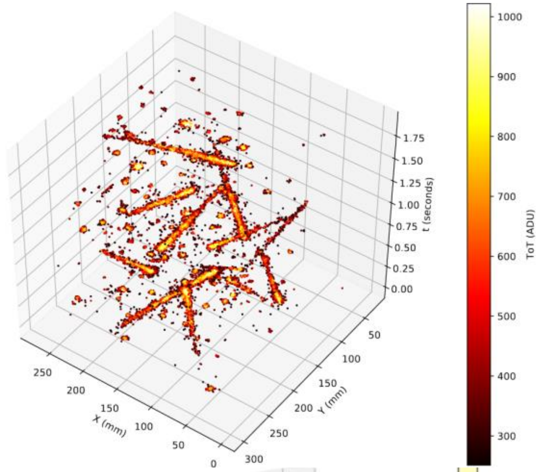
ARIADNE: Optical dual-phase LArTPC with TPX3Cam

detector at Liverpool

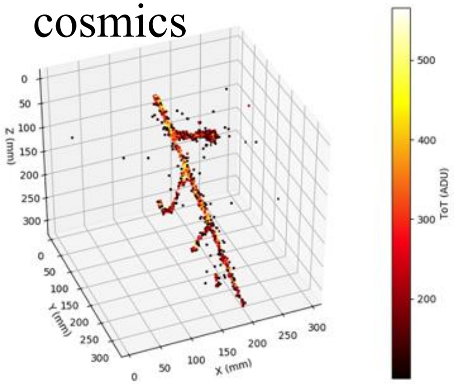


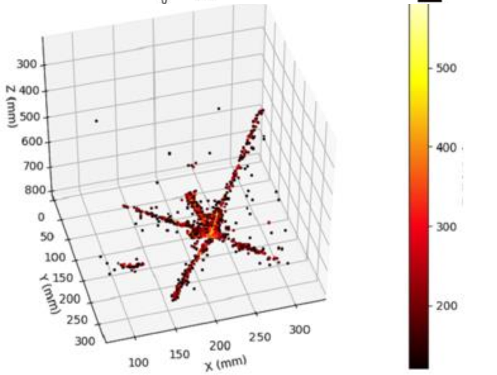
FR4 THGEM, 0.5mm hole

1.75 sec streaming



cosmics



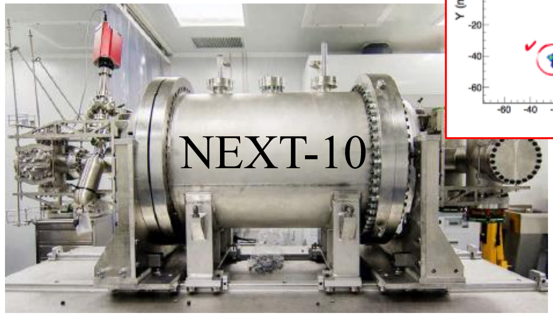


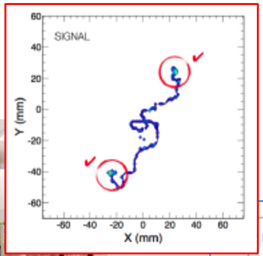
electroluminescent

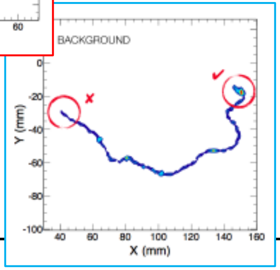
TPC characteristics:

- Fast TPX3 cameras photograph the S2 light generated in THGEM holes.
- Raw 3D data from a single device. One camera can cover 1 m x 1m LAr column @4mm/pixel resolution, ideal for large neutrino experiments.
- Amenable to any type of optical chamber (in fact, LAr is possibly the most difficult case)

Instruments 2020, 4, 35
(and references therein)







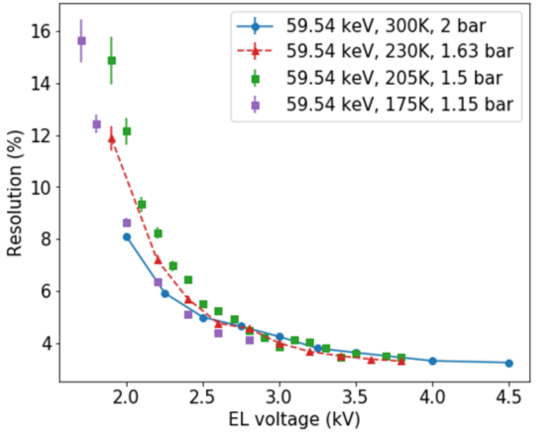
TPC characteristics and performance:

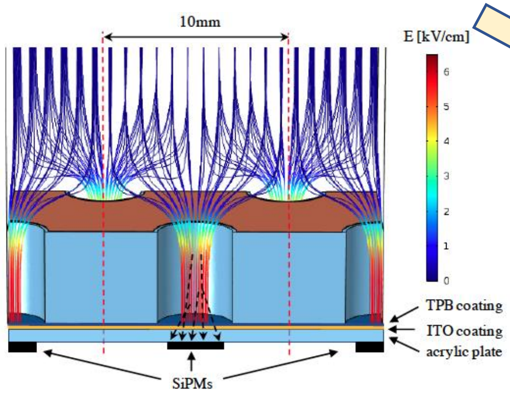
- 3D-reconstruction of tracks through SiPM plane.
- Strong $\beta\beta0\nu$ topological signature (demonstrated).
- <1% energy resolution (demonstrated).
- Technology frozen, NEXT-100 under construction.

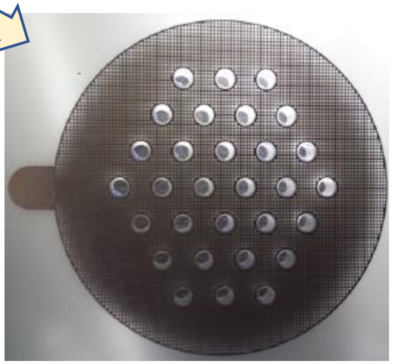
R&D towards NEXT-1Ton (fully explore inverted hierarchy)

- Develop a scheme for Ba-tagging.
- Consider low-diffusion mixtures (Xe/He, Xe/CH_4).
- Study detector cool down (allows replacing PMs by SiPMs, enables higher gas mass for the same pressure, lower outgassing).
- New EL-structures for better scalability, stability and yield.

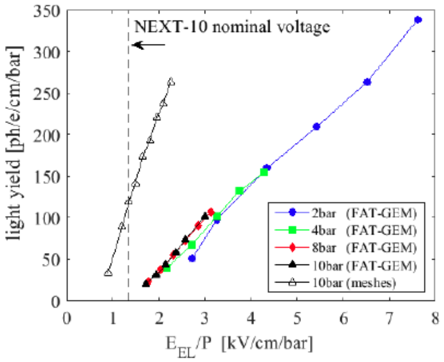
cold xenon



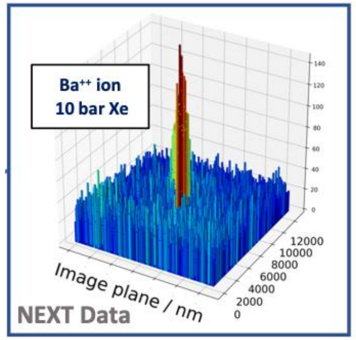




arXiv:1907.03292

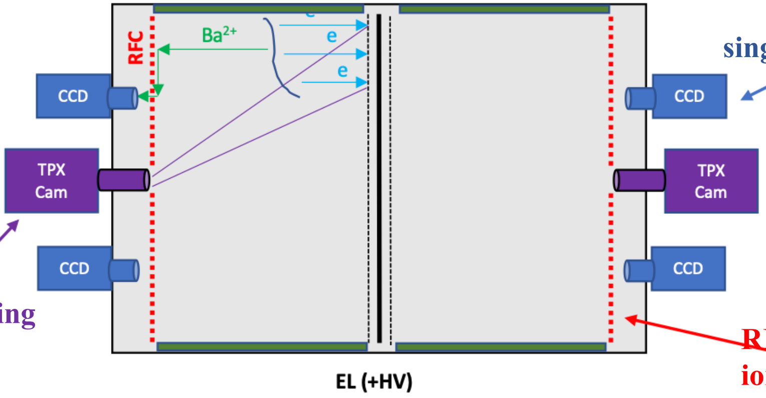


Barium tagging (find 1atom in 1ton of atoms!)



JINST 11 (2016) no.12, P12011
Phys. Rev. Lett 120, 132504 (2018)
Phys.Rev.A 97 (2018) 6, 062509
Nature Sci Rep 9, 15097 (2019)
Nature 583, 48–54 (2020)
JINST 15 (2020) 04, P04022
ACS Sens. 6, 1, 192–202 (2021)

CRAB concept



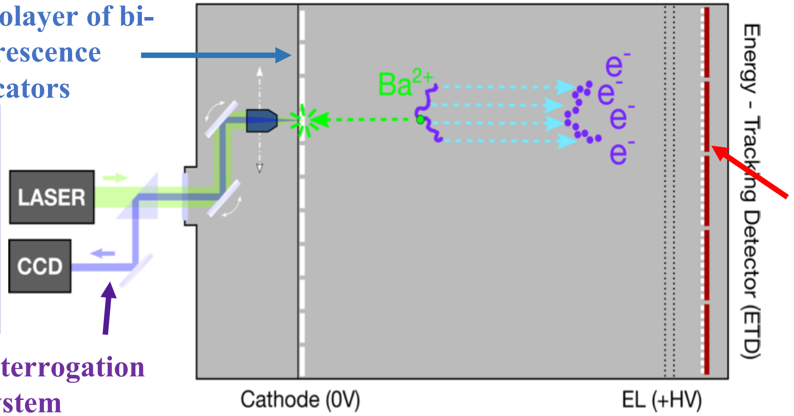
single Ba^{2+} ion tagging

direct UV camera imaging

RF carpet ion transport in xe gas

BOLD concept*(ERC-funded)

monolayer of bi-fluorescence indicators



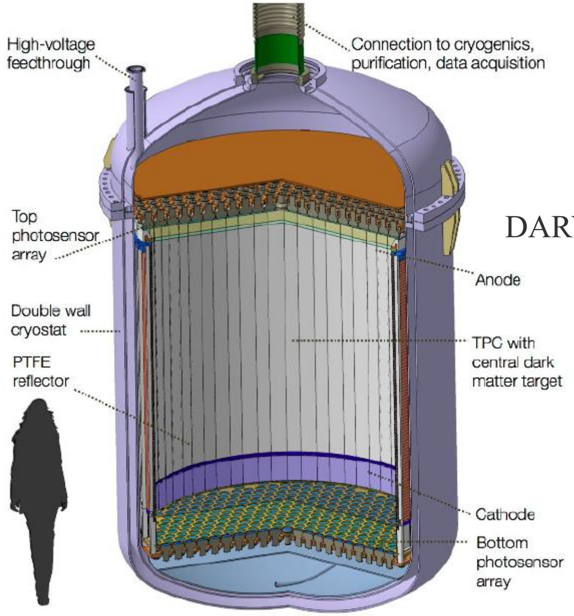
interrogation system

SiPM plane for imaging and to reconstruct energy

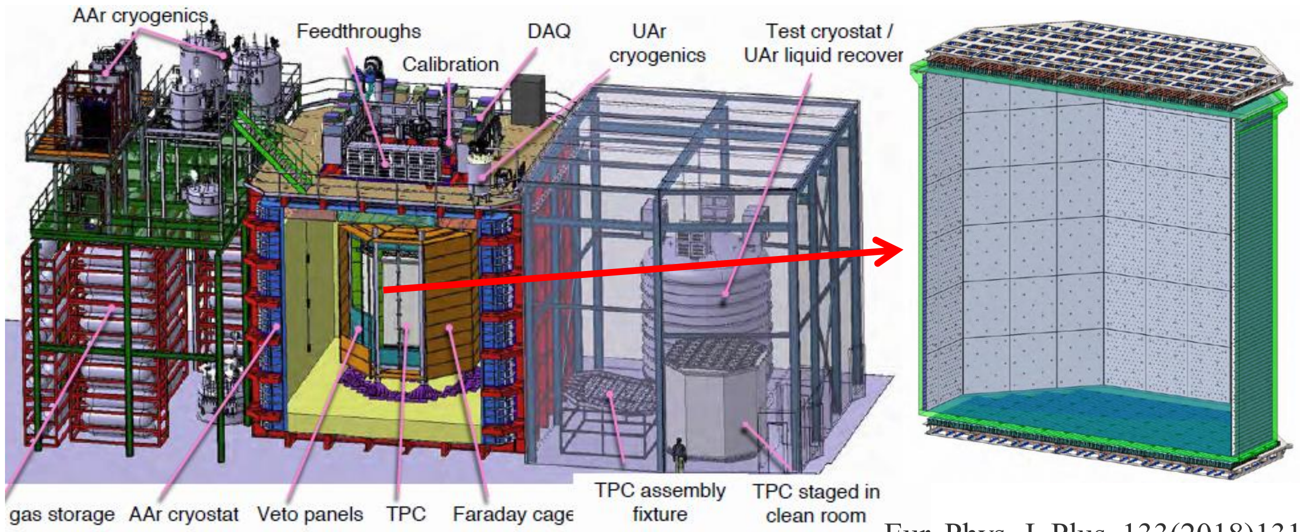
electroluminescent

DARWIN ⟺ the ultimate dual-phase noble-element detectors? ⟺ DarkSide20 and ARGO

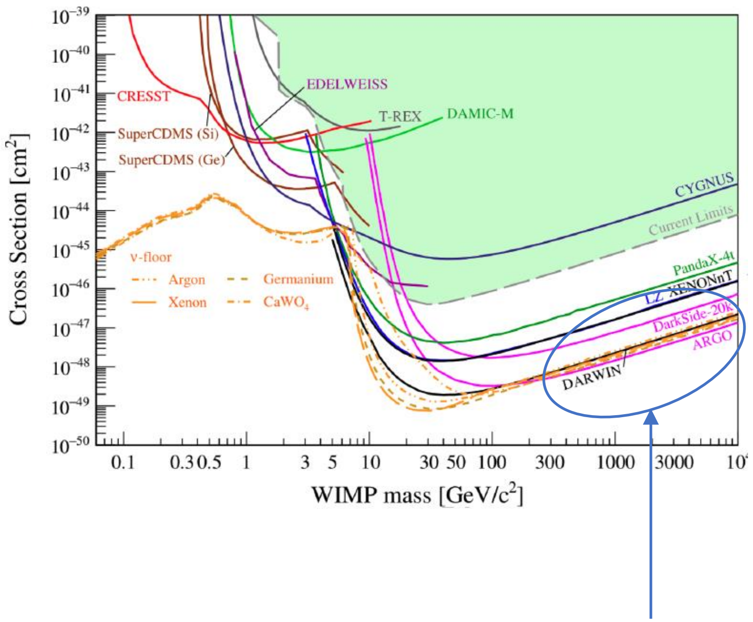
many more details in L. Baudis
https://indico.cern.ch/event/994687/



DARWIN, JCAP 1611(2016)017



Eur. Phys. J. Plus, 133(2018)131



Goal:

- Reach sensitivities down to the neutrino floor.

TPC characteristics:

- Particle discrimination by S1/S2.
- Drift/diameter: 2.6 m / 2.6 m.
- Mass: 40 t.

R&D:

- Learning from large experience with XENON detectors and up-scale solutions. Use PMs.
- Robust electrode design (up to 50kV).
- Reduce backgrounds (Rn, n's, γ's).
- Achieve good liquid purity.

Goal:

- Reach sensitivities down to the neutrino floor.

TPC characteristics:

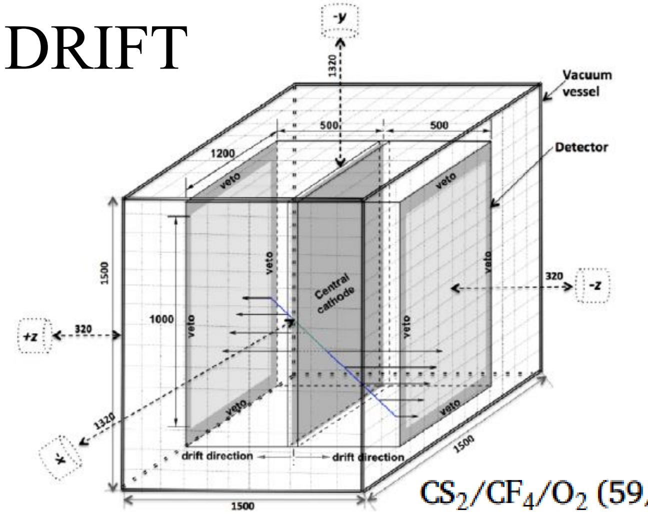
- Particle discrimination by S1/S2 and pulse shape.
- Drift/diameter: 3.5 m / 3.5 m.
- Mass: 51.7 t.

R&D:

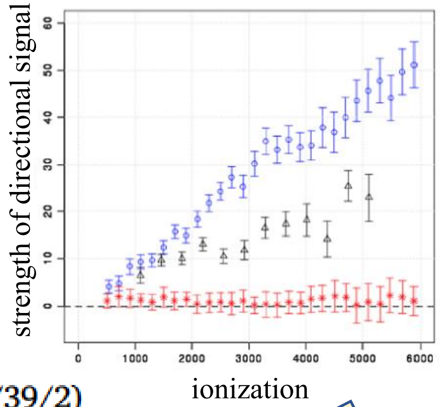
- Instrumented with SiPMs, in assemblies called photodetector modules (PDMs), similar to a 3” PMT.
- Possible thanks to the discovery of low radioactivity argon in underground CO_2 wells (UAr) with an activity 1400 (or more) times lower than atmospheric.

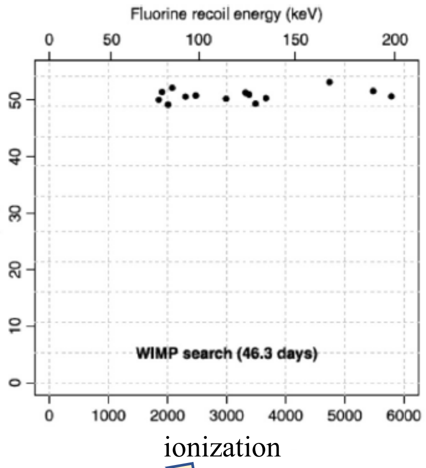
electroluminescent

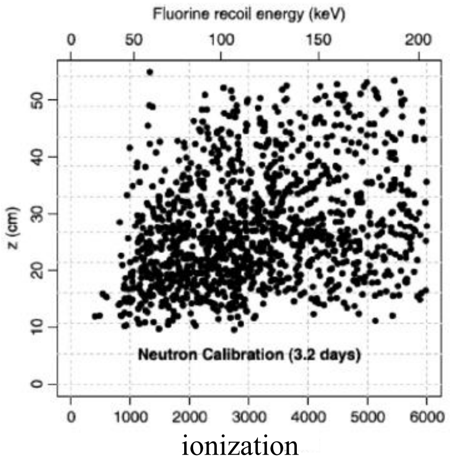
DRIFT

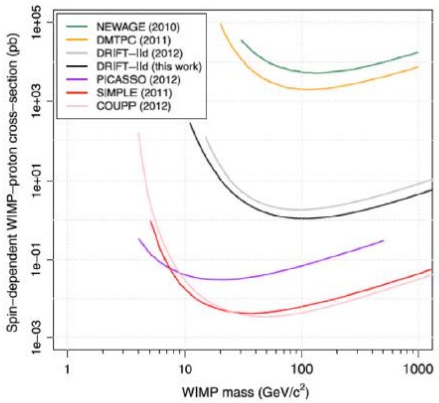


$CS_2/CF_4/O_2$ (59/39/2)









DRIFT (part of the global CYGNUS effort for directional Dark Matter detection)

Goal:

- Obtain the best possible electron/nuclear recoil separation capability and directionality at ~20-40 mbar.

TPC characteristics:

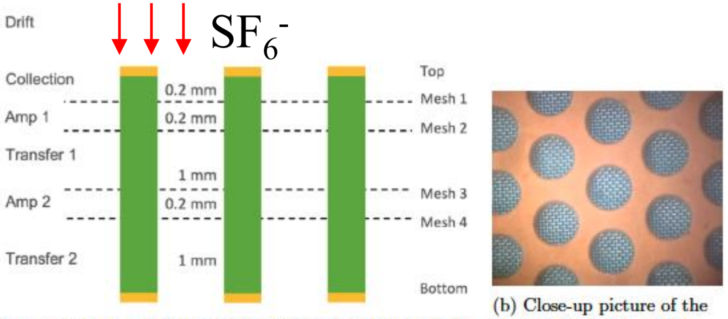
- Read out with criss-crossing wires.
- Use negative ions to reduce diffusion and fine-grained. longitudinal information for estimating track direction.
- Use minority carriers for z-fiducialization (e.g., O_2^-).

R&D towards a DDM observatory:

- Replace CS_2 by SF_6 mixtures (works in pure gas since SF_5^- allows event fiducialization, and higher number of F-atoms),
- Multiplication in SF_6 more difficult due to higher electron afinity.
- Requires developing new amplification structures!

MM-ThGEM

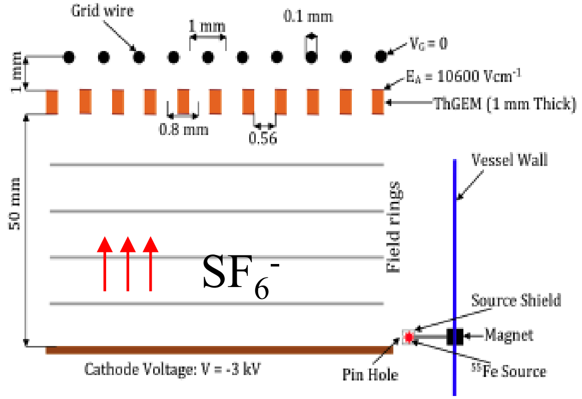
SF_6^-

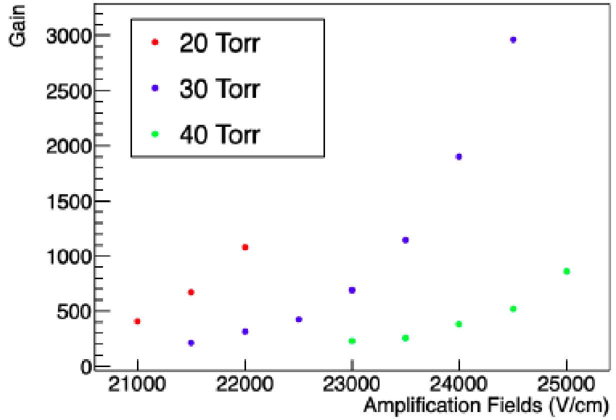


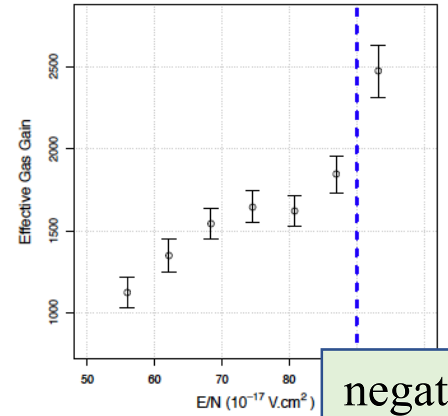
(a) Cross-section of the MMThGEM with the field names (left), plane names (right) and the gap widths (centre-left)

(b) Close-up picture of the MM-ThGEM holes from above

ThGEM + MWPC



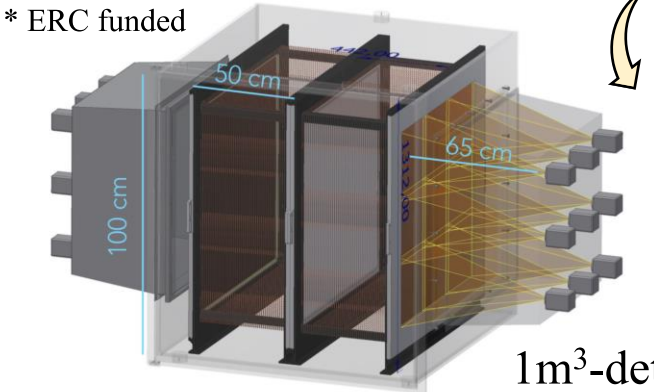




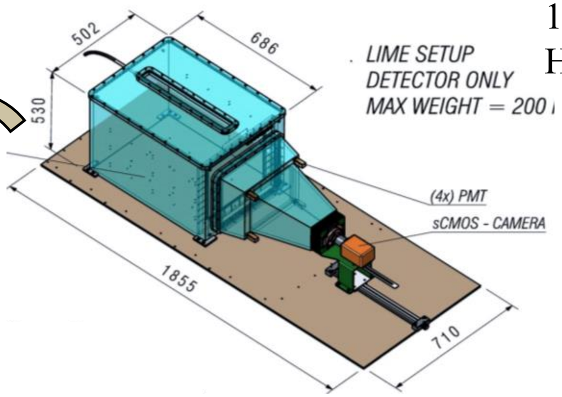
negative ions

CYGNO INITIUM

* ERC funded

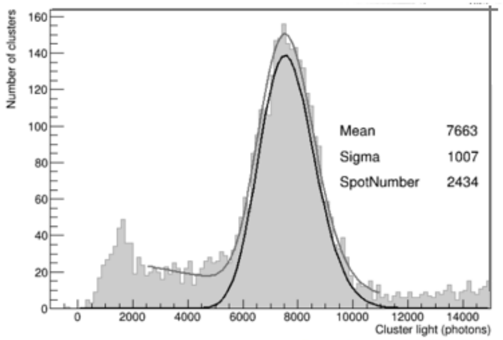


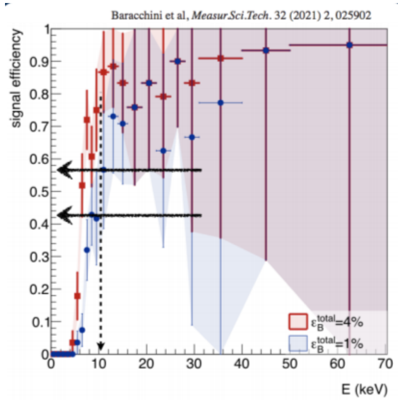
1m^3-detector



130 x 130 μm^2 effective pixel size

He/CF_4 (60/40) at 1bar





A sizeable NR detection efficiency was measured:

- **40%** at 6 keV;
- **55%** at 10 keV;

In the same conditions more than **99% (95%)** **^{55}Fe photons** were **rejected**

CYGNO (part of the global CYGNUS effort for directional Dark Matter detection)

Goal:

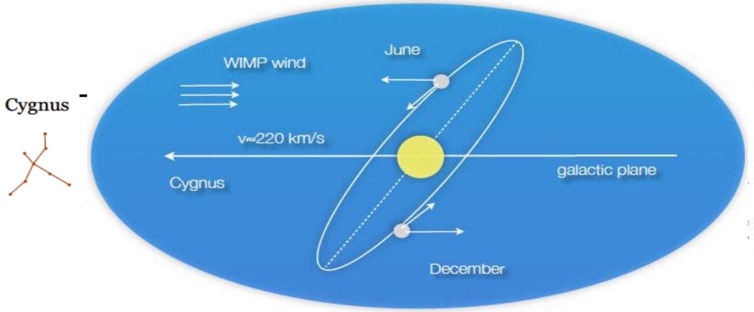
- Obtain good electron/nuclear recoil separation at ~1bar.
- Systematically study He/CF_4/SF_6 mixtures.

TPC characteristics:

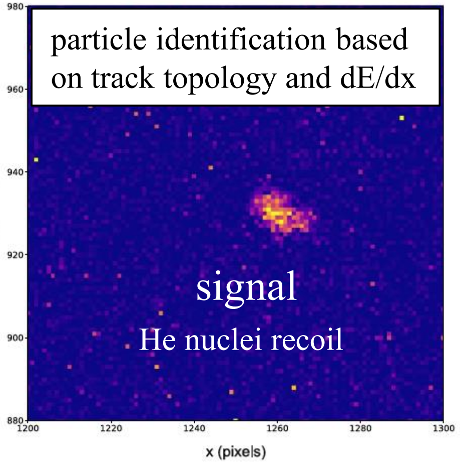
- Optically read (2D readout).
- 1m^3-funded TPC based on tested technology.

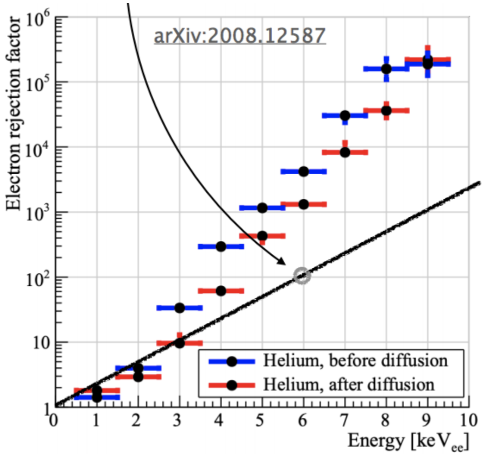
R&D towards a DDM observatory:

- Scintillation in He:CF_4:SF_6.
- Optimization of secondary scintillation.
- Study H-based mixtures for low WIMP mass sensitivity.
- Apply machine learning techniques to discrimination.
- Improvements on camera noise, sensor size, and wavelength will be important. Especially important is tts radiopurity!.

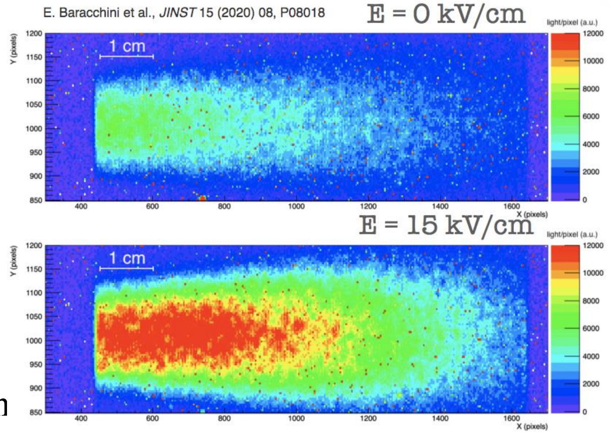


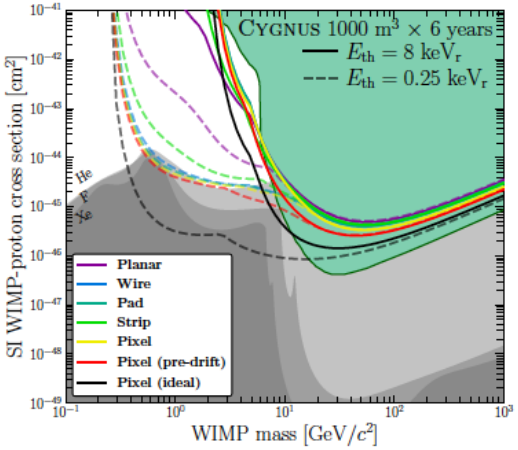
$$v(t)_{DM} = v_{sun} + v_{orb}\, cos\gamma\, cos(\omega(t-t_0))$$





electroluminiscence signal in CF_4-based mixtures (x5.7 enhancement)





Measure. Sci. Tech. 32(2021)2, 025902
JINST 15(2020)08, P080180
JINST 13(2018)04, P04022
arXiv:2008.12587

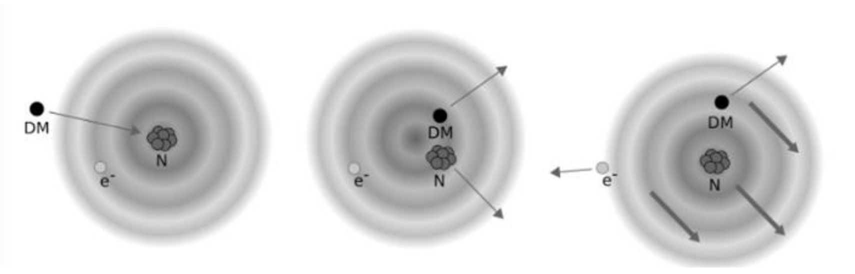
optical, (+ negative ions?)

MIGDAL
Migdal In Galactic Dark mAtter expLoration

Optical Time Projection Chamber for observation of the Migdal effect in nuclear scattering

UNIVERSITY OF BIRMINGHAM | GDD Gas Detectors Development Group | HELSINKI INSTITUTE OF PHYSICS | Imperial College London | LIP | THE UNIVERSITY OF NEW MEXICO | UNIVERSITY OF OXFORD | ROYAL HOLLOWAY UNIVERSITY OF LONDON | Science & Technology Facilities Council Rutherford Appleton Laboratory | The University Of Sheffield.

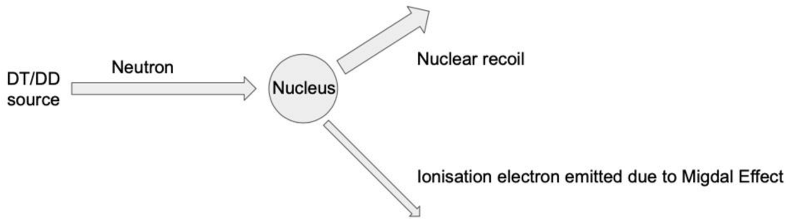
atomic effect predicted by A. Migdal in 1939

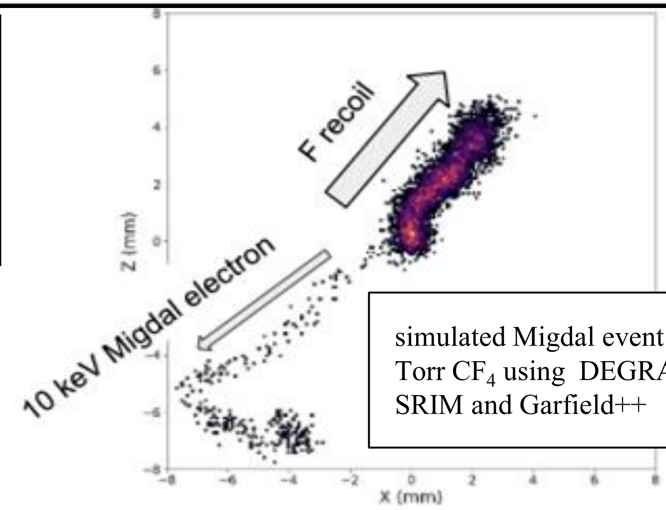


Migdal Effect - nucleus moves relative to the electron cloud. Individual electron might be ejected leading to ionisation.

Goal:

➢ Observation of two tracks (Migdal electron and nuclear recoil) originating from the same vertex in a low pressure gaseous detector using a high intensity DT/DD neutron generator.





simulated Migdal event in 50 Torr CF_4 using DEGRAD, SRIM and Garfield++

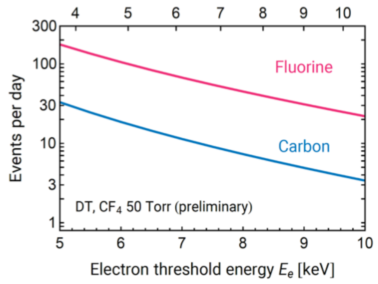
Regular Article - Experimental Physics | Open Access | Published: 30 March 2018

Migdal effect in dark matter direct detection experiments

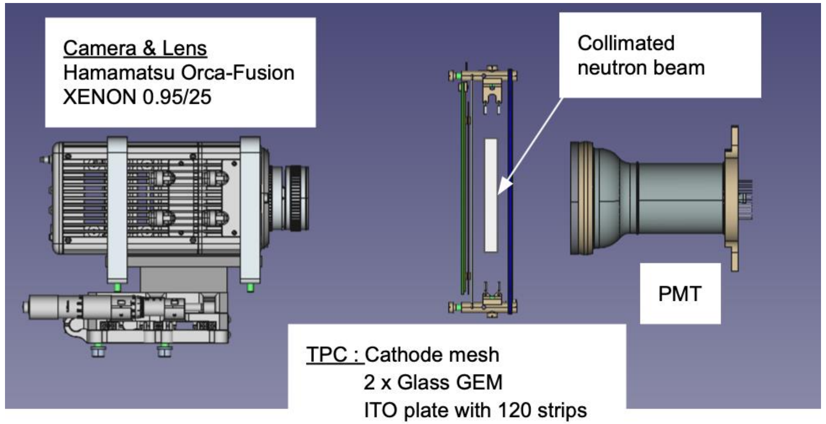
Masahiro Ibe, Wakutaka Nakano, Yutaro Shoji & Kazumine Suzuki

Journal of High Energy Physics **2018**, Article number: 194 (2018) | Cite this article

Expected number of Migdal events in CF_4 using DT generator



Taking into account energy distribution and rates of the events with C and F recoils in the fiducial region over one day of exposure to neutron from DT generator.

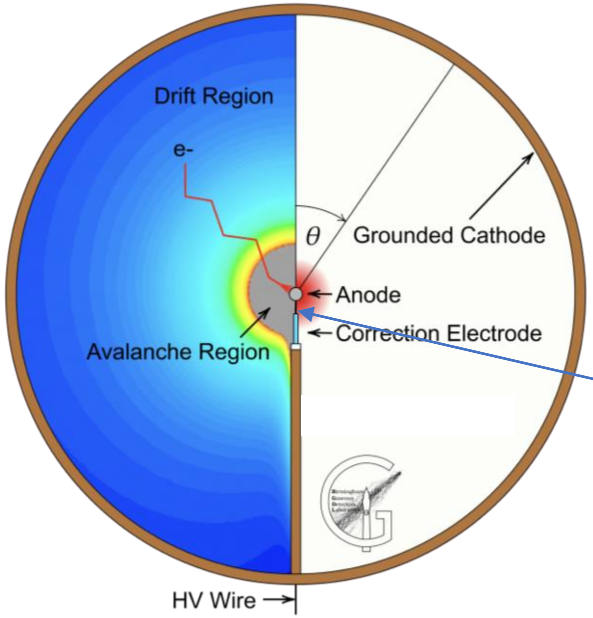


Dark Matter searches and Migdal Effect
-> sensitivity extension to low mass region

Huge attention by DM community with almost 100 citations of Ibe's paper since 2018 (this includes major experiments searching for WIMPs)

optical, (+ negative ions?)

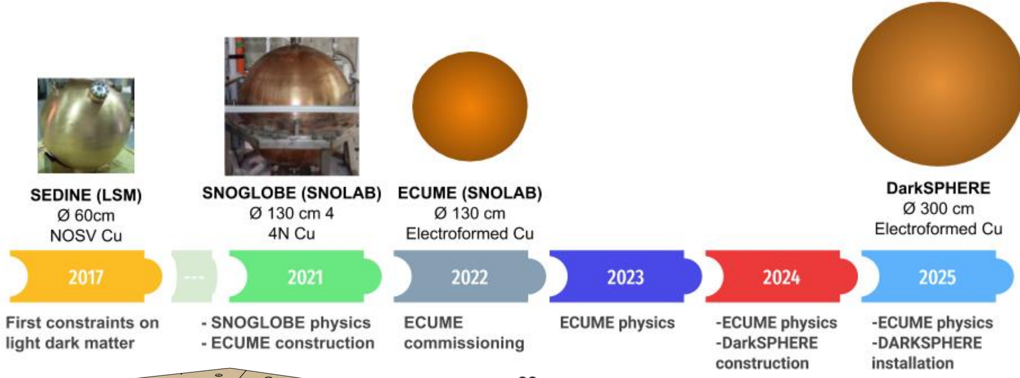
Spherical Proportional Detector

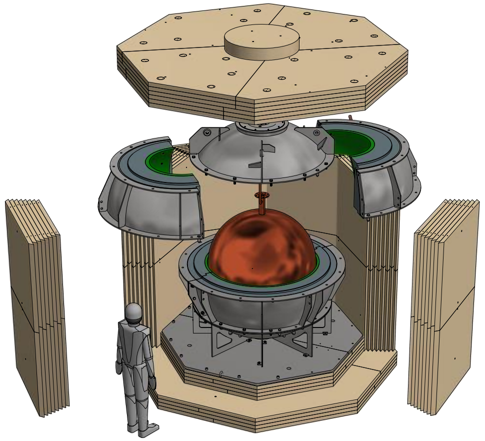


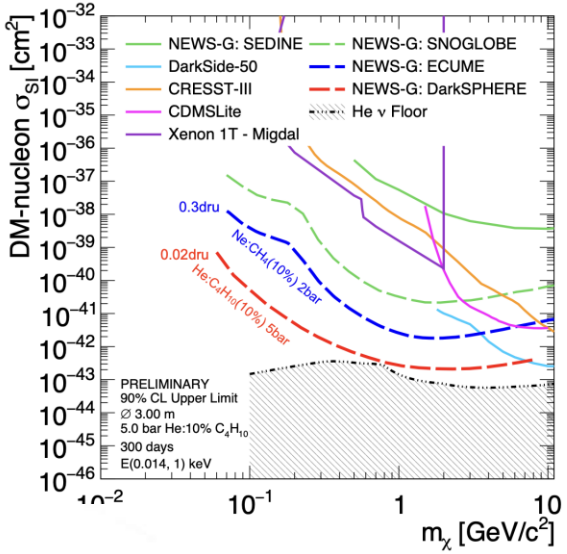
$$E(r) = \frac{V_0}{r^2}\frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

r_A = *anode ball radius*
r_C = *cathode radius*

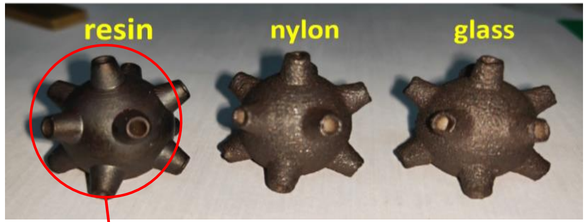
C≈ r_a= 1 mm < 1pF







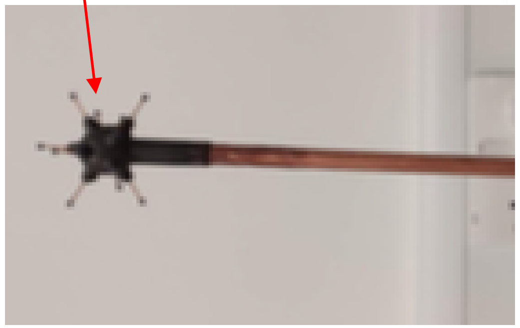
central electrode is key
(years of evolution!



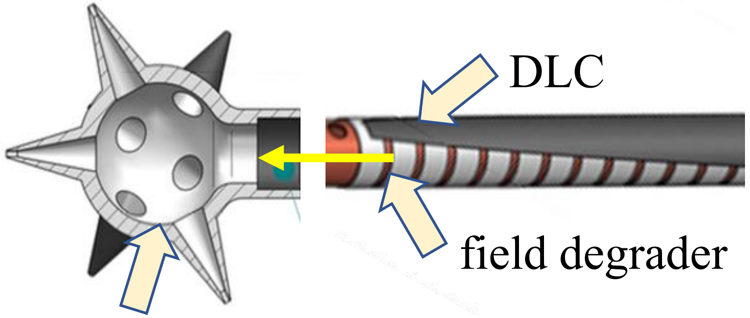
main characteristics (in the inventor's words!):

- Simple and cheap.
- Large volume (i.e., compatible with pressurization).
- Single channel read-out.
- Robustness.
- Good energy resolution.
- Low energy threshold.
- Efficient fiducial cut.
- Low background capability.

⟶ Very suitable for rare-event searches!!



ACHINOS (v.1)



adaptative field (high enough field both close and far from the anode)

ACHINOS (new version)

JINST 3 (2008) P09007
JINST 15 (2020) P11023

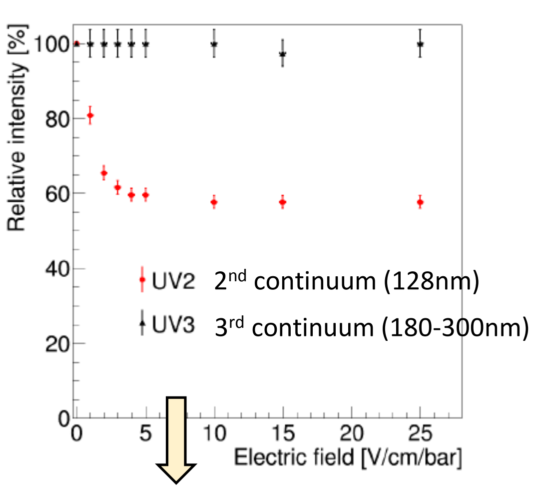
spherical

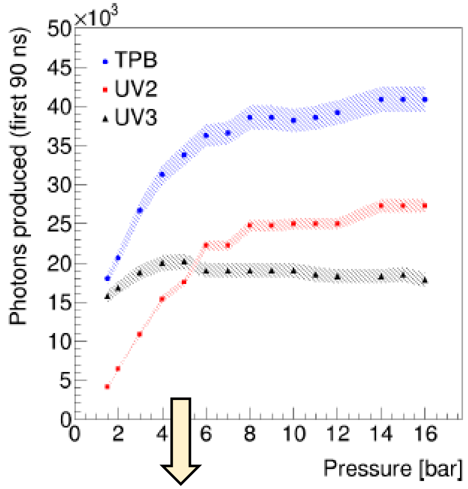
Last: some fresh new technologies/ideas/techniques

a) Scintillation in pressurized argon more complex than generally assumed!

scintillation response for α's

arXiv:2012.08262v1



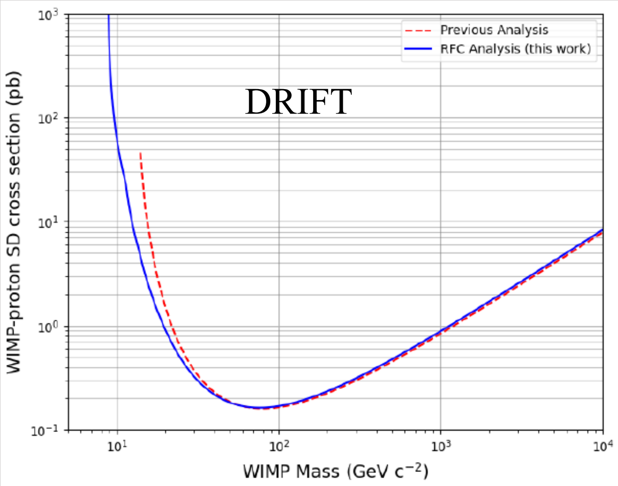


for the same released energy the ratio 2^{nd} / 3^{rd} is particle dependent

a large fraction of the prompt scintillation component is not emitted in the 2^{nd} continuum band!

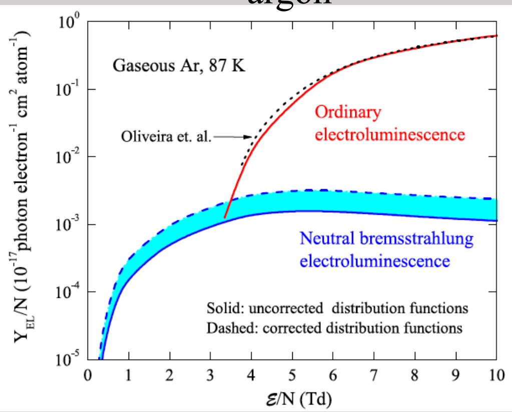
c) Use machine-learning algorithms to improve sensitivity to low energy nuclear recoils

arXiv:2103.06702

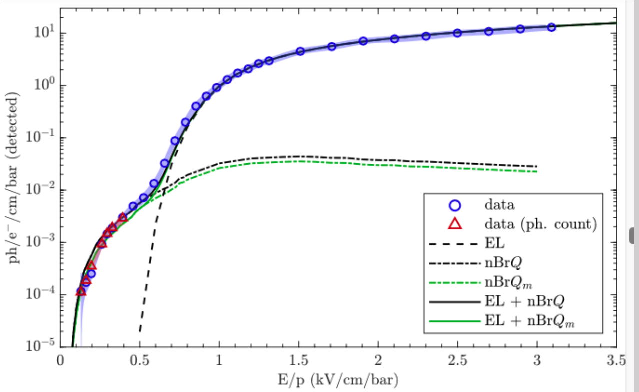


b) Neutral bremsstrahlung: the dominant mechanism of secondary scintillation at low fields (a phenomenon looking for an application!)

argon



xenon



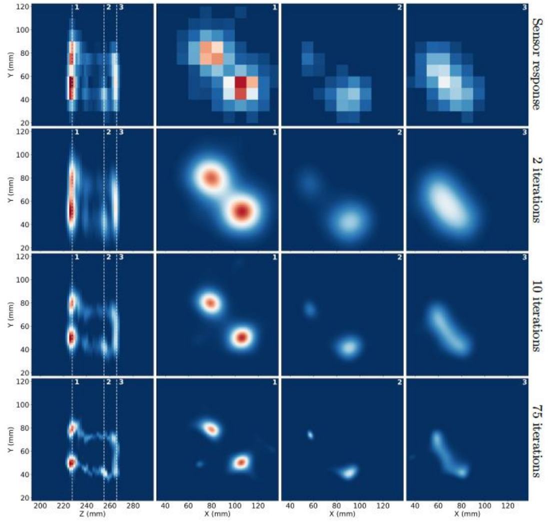
Astrop. Phys. 103(2018)29-40

NIM A, 958(2020)162432

Submitted to PRX

(C. Henriques private communication)

d) Apply deconvolution from point spread function and diffusion (requires an exquisite understanding of the detector response and specific algorithms to avoid the effect of noise).



works better for NEXT task than deep-neural networks analysis!

arXiv: 2102.11931

thanks for your attention